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Gu et al.

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(54) **DC/DC CONVERTER WITH RESONANT CONVERTER STAGE AND BUCK STAGE AND METHOD OF CONTROLLING THE SAME**

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(51) **Int. Cl.**

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H02M 3/156	(2006.01)
H02M 3/337	(2006.01)
H02M 1/00	(2006.01)
H02M 7/48	(2006.01)

(52) **U.S. Cl.**

CPC ***H02M 3/156*** (2013.01); ***H02M 3/3376*** (2013.01); *H02M 2001/007* (2013.01); *H02M 2007/4815* (2013.01)

USPC **363/95**

(58) **Field of Classification Search**

USPC 363/20, 21.01, 21.02, 95, 97; 323/265, 323/267, 273, 282, 283, 285

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,518,263	B2 *	4/2009	Gan et al.	307/32
8,587,963	B2 *	11/2013	Nan et al.	363/21.02
2008/0055941	A1 *	3/2008	Victor et al.	363/17
2008/0094860	A1 *	4/2008	Falk	363/17
2010/0182803	A1 *	7/2010	Nan et al.	363/21.02
2012/0081200	A1 *	4/2012	Silva	336/20
2012/0081204	A1 *	4/2012	Garrity et al.	336/221
2012/0081933	A1 *	4/2012	Garrity	363/37
2012/0081934	A1 *	4/2012	Garrity et al.	363/37
2013/0229834	A1 *	9/2013	Garrity et al.	363/37
2014/0153290	A1 *	6/2014	Li et al.	363/17

* cited by examiner

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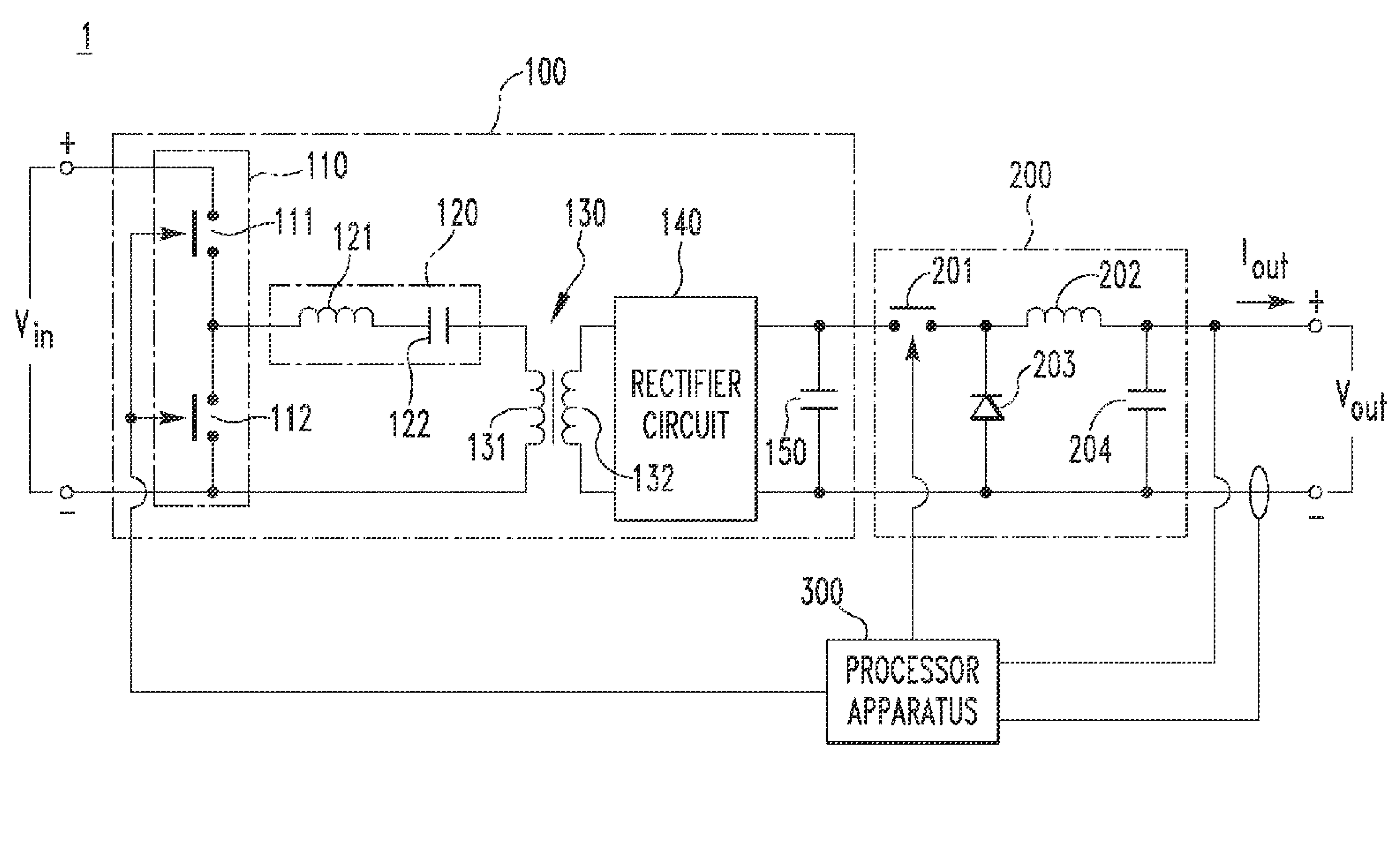
(57) **ABSTRACT**

A direct current to direct current (DC/DC) converter includes a resonant converter stage, a buck stage, and a processor apparatus. The resonant converter stage includes a bridge circuit. The buck stage is configured to output an output voltage and an output current, is electrically connected in series with the resonant converter stage, and includes a buck switch. The processor apparatus is configured to sense the output voltage and the output current, and, based on the sensed output voltage and the sensed output current, to perform one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage by controlling the switching frequency of the bridge circuit.

20 Claims, 5 Drawing Sheets



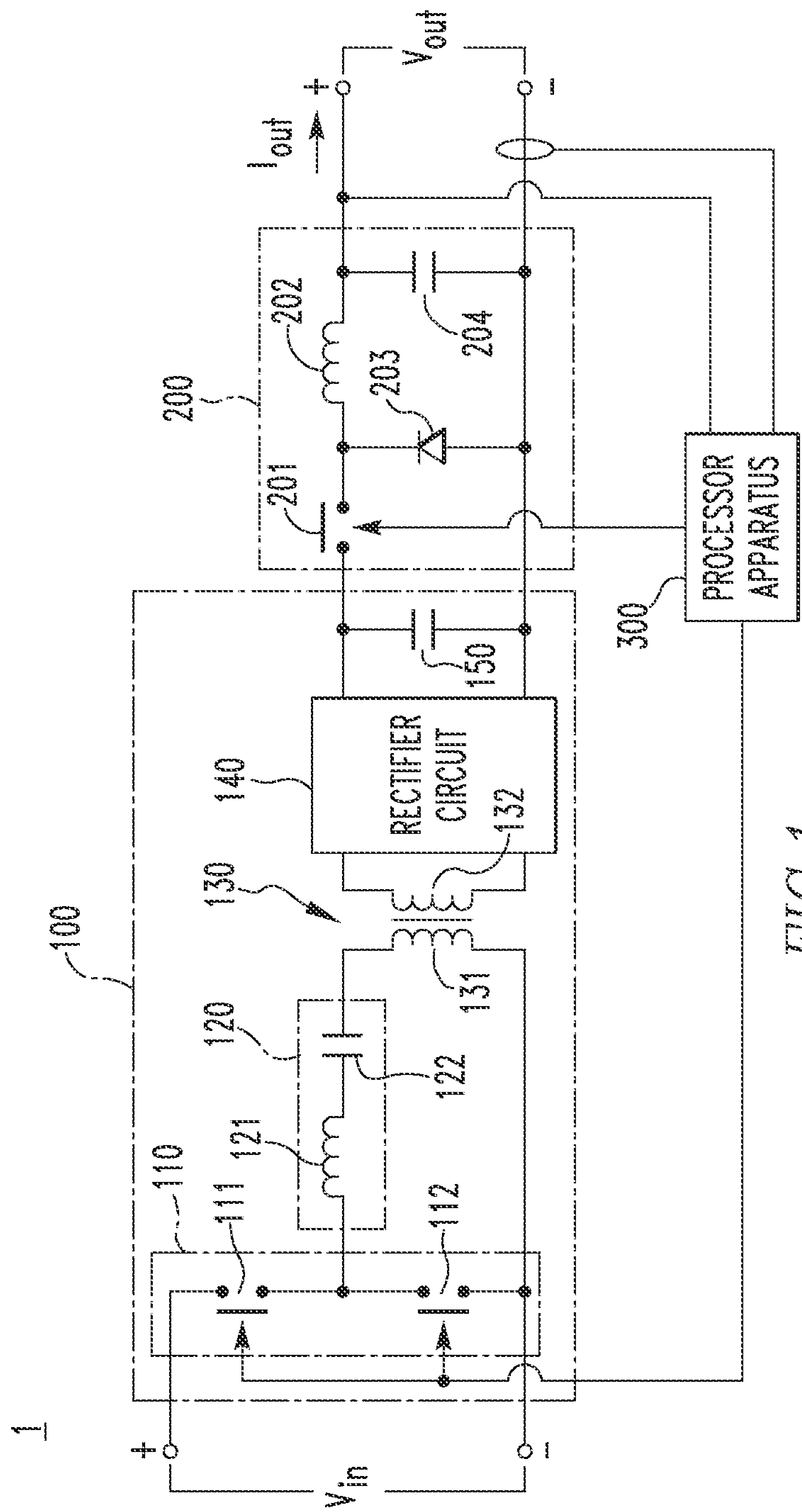

1
100
110
111
112
120
121
122
130
131
132
140
RECTIFIER CIRCUIT
150
200
201
202
203
204
300
PROCESSOR APPARATUS
V_{in}
V_{out}
I_{out}

FIG. 1

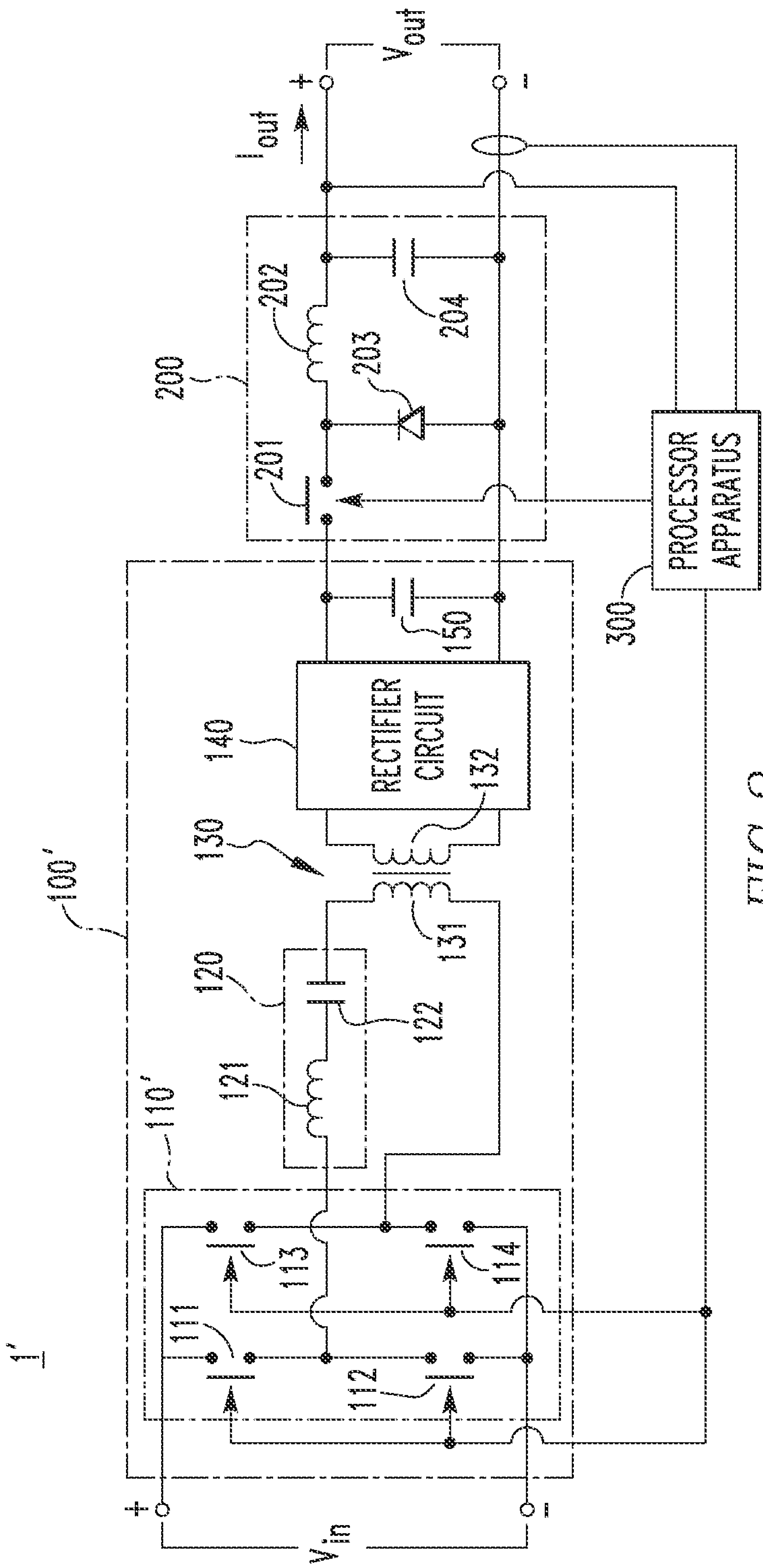

1'
100'
110'
111
112
113
114
120
121
122
130
131
132
140
RECTIFIER CIRCUIT
150
200
201
202
203
204
300
PROCESSOR APPARATUS
V_{in}
V_{out}
I_{out}
+
-

FIG. 2

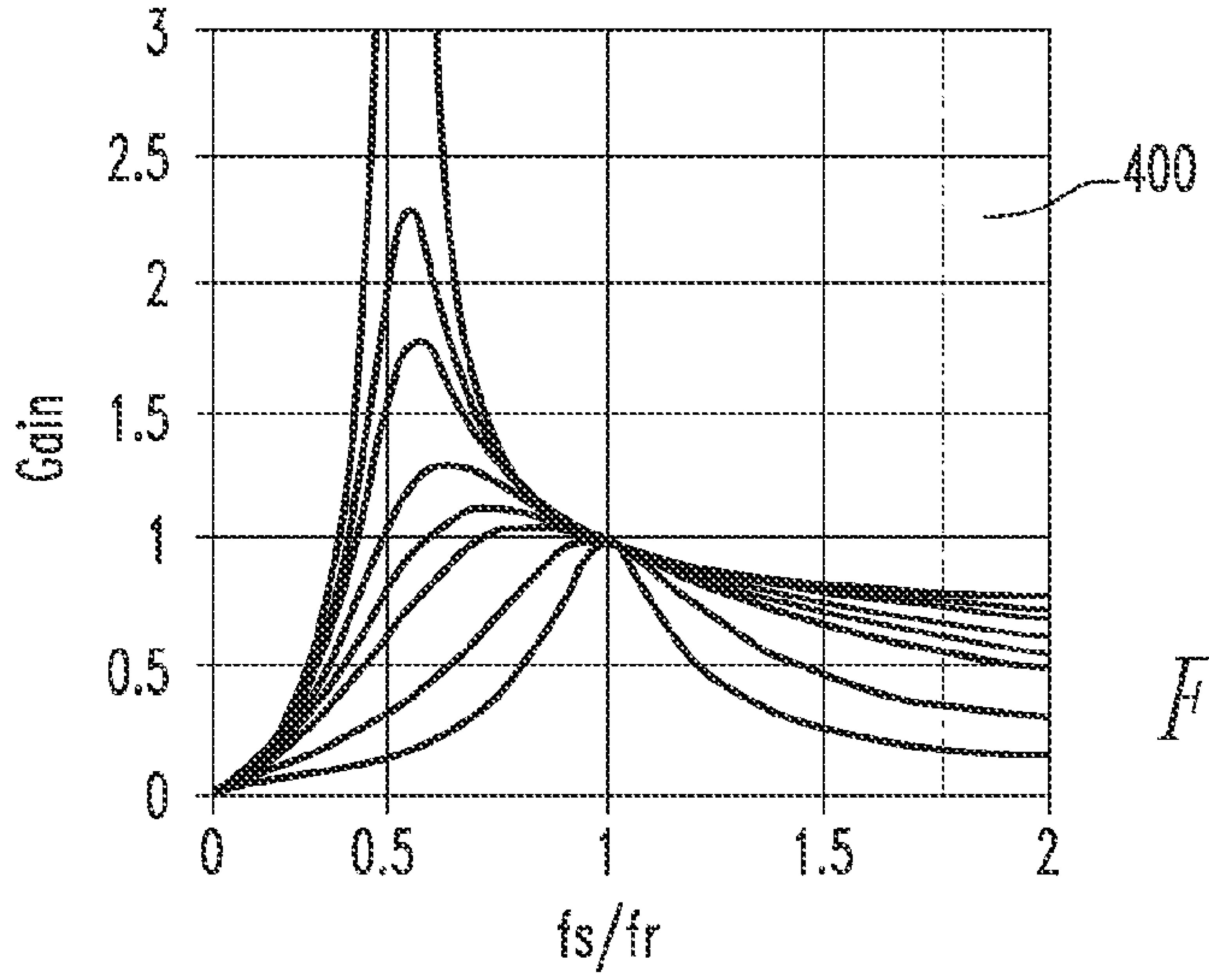

3
2.5
2
1.5
1
0.5
0
Gain
0
0.5
1
1.5
2
fs/fr
400

FIG. 3A

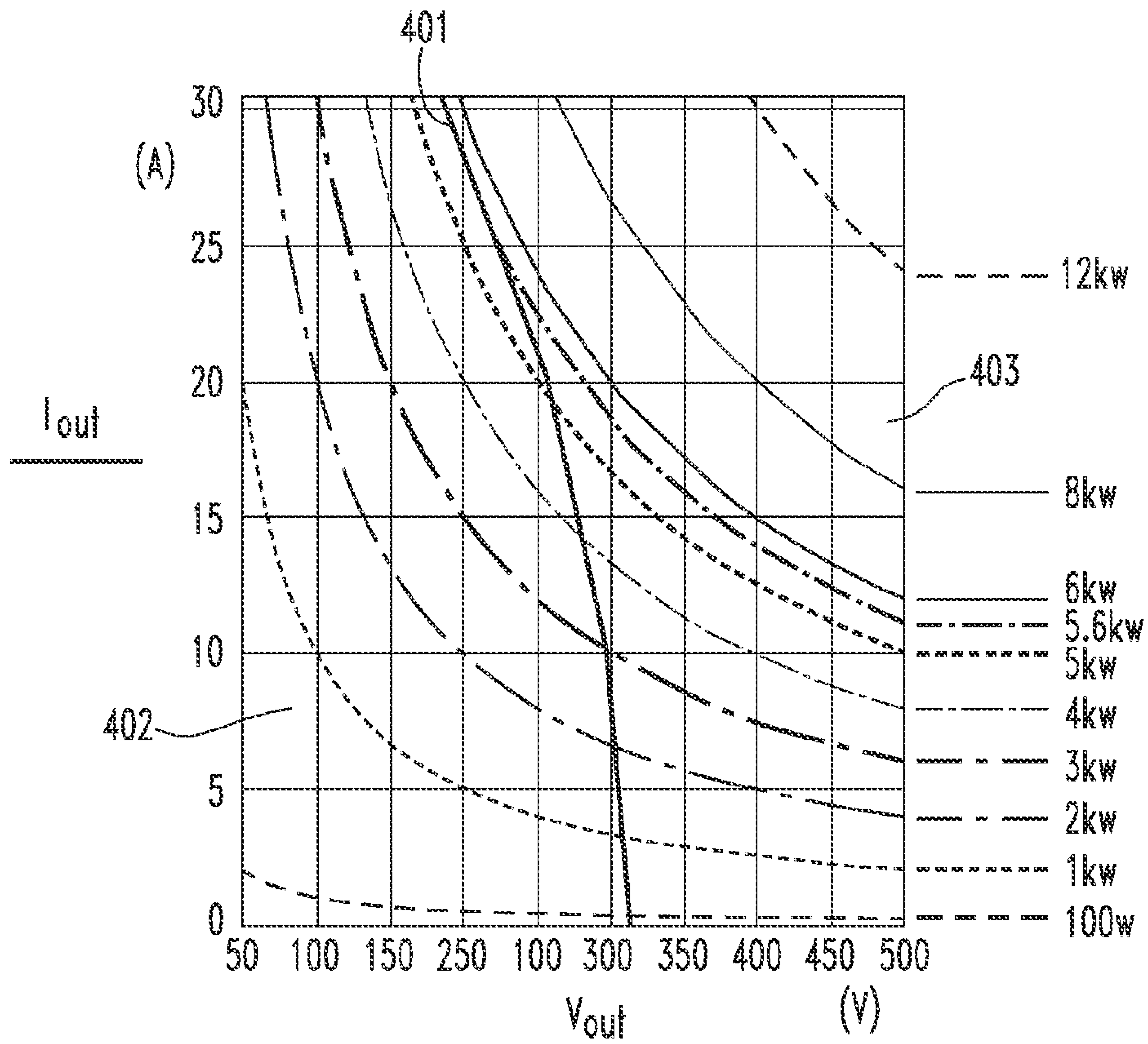

401
30
25
20
15
10
5
0
(A)
I_{out}
402
403
50
100
150
250
100
300
350
400
450
500
V_{out}
(V)
12kw
8kw
6kw
5.6kw
5kw
4kw
3kw
2kw
1kw
100w

FIG. 3B

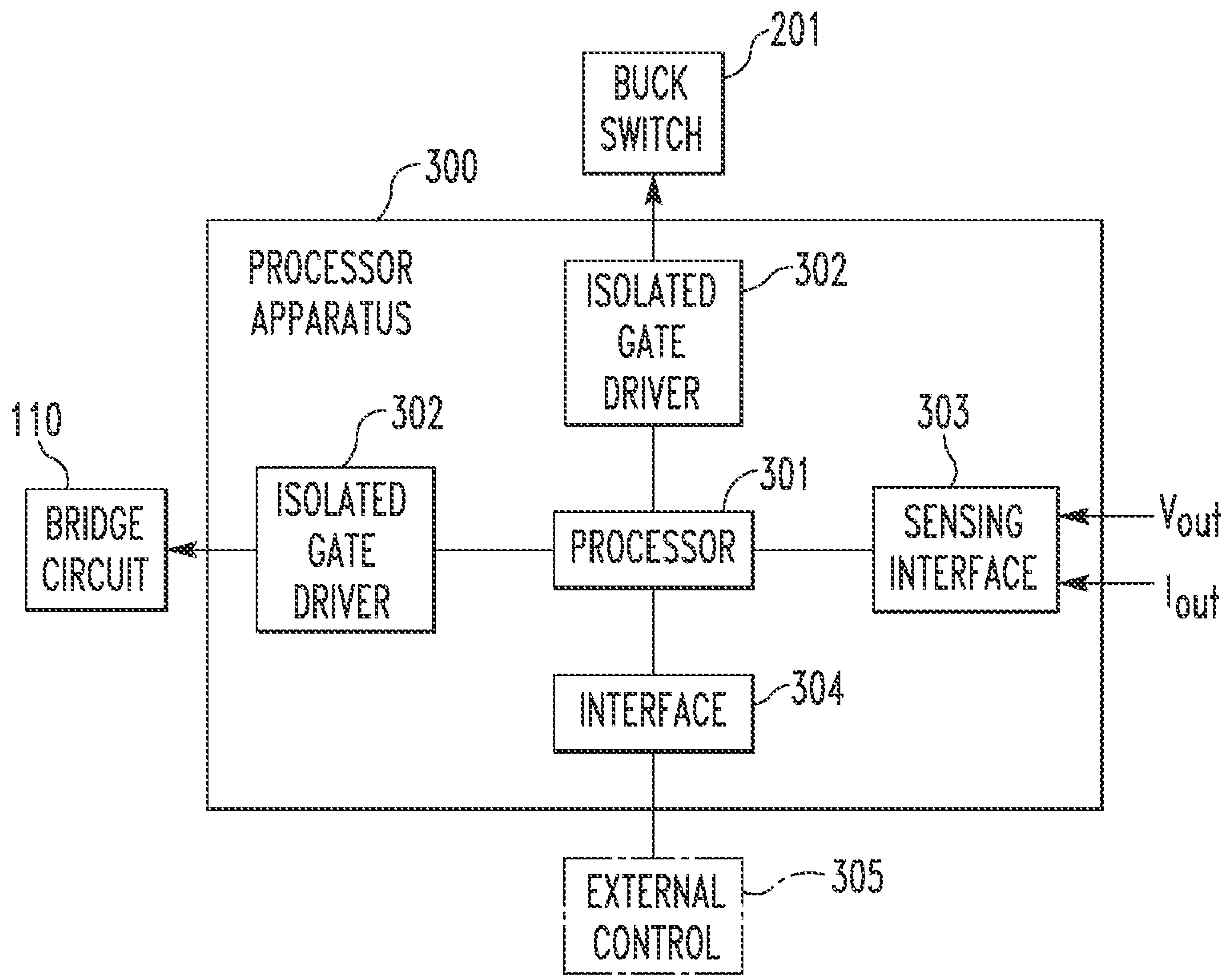

201
BUCK SWITCH
300
PROCESSOR APPARATUS
302
ISOLATED GATE DRIVER
110
BRIDGE CIRCUIT
302
ISOLATED GATE DRIVER
301
PROCESSOR
303
SENSING INTERFACE
V_{out}
I_{out}
304
INTERFACE
305
EXTERNAL CONTROL

FIG. 4

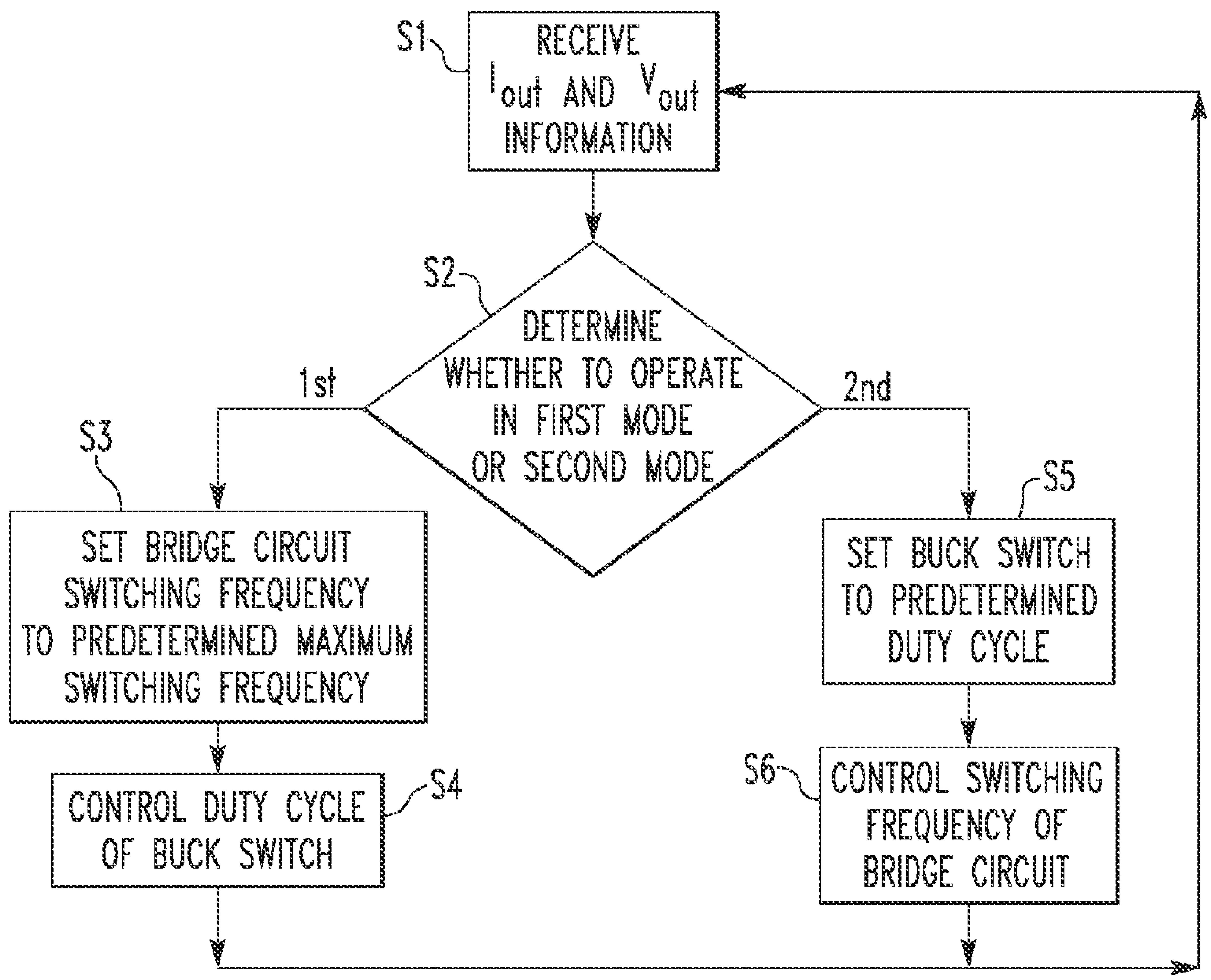

S1
RECEIVE
I_{out} AND V_{out}
INFORMATION
S2
DETERMINE
WHETHER TO OPERATE
IN FIRST MODE
OR SECOND MODE
1st
2nd
S3
SET BRIDGE CIRCUIT
SWITCHING FREQUENCY
TO PREDETERMINED MAXIMUM
SWITCHING FREQUENCY
S4
CONTROL DUTY CYCLE
OF BUCK SWITCH
S5
SET BUCK SWITCH
TO PREDETERMINED
DUTY CYCLE
S6
CONTROL SWITCHING
FREQUENCY OF
BRIDGE CIRCUIT

FIG. 5

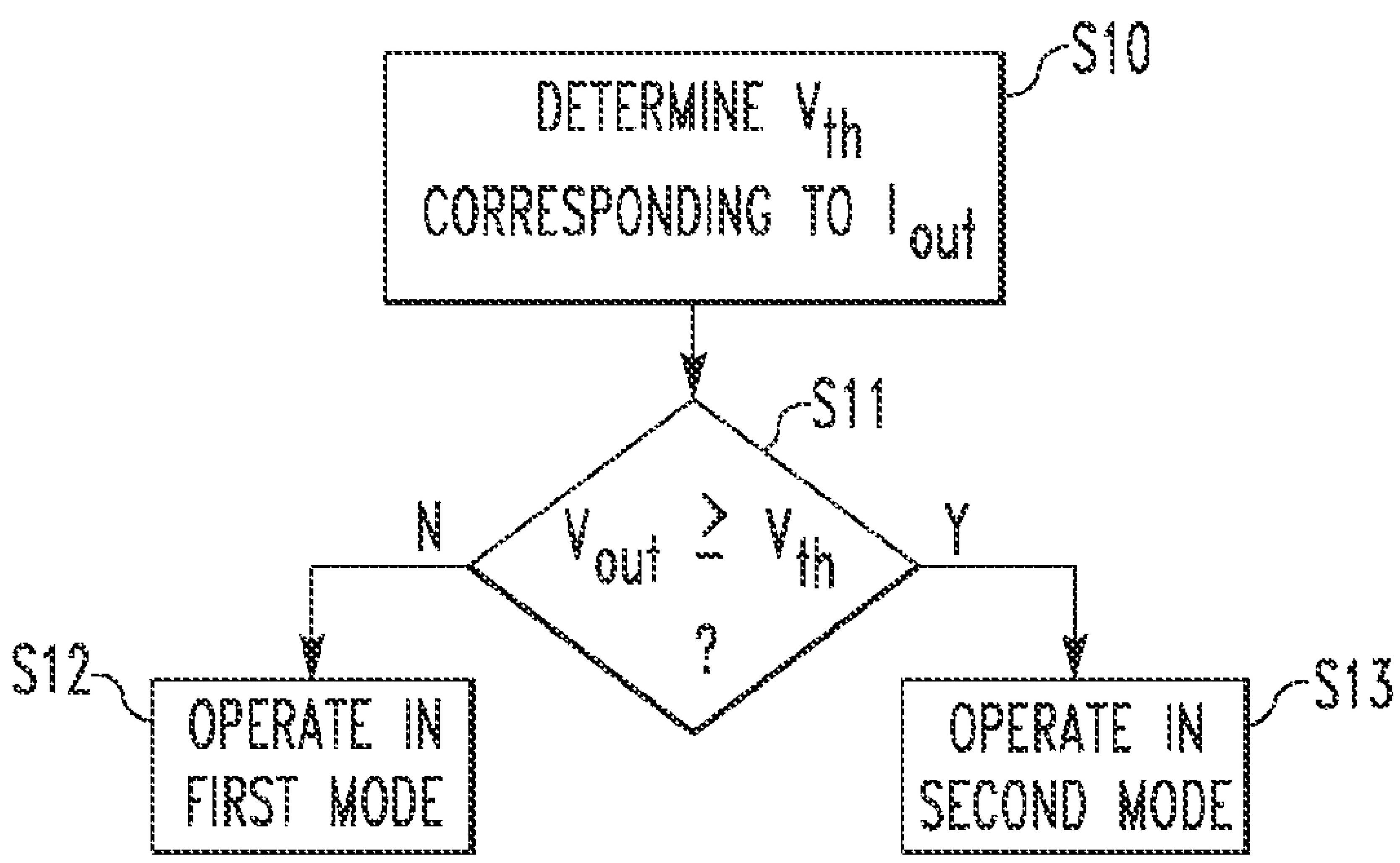

S10
DETERMINE V_{th}
CORRESPONDING TO I_{out}
S11
$V_{out} \geq V_{th}$
?
N
Y
S12
OPERATE IN
FIRST MODE
S13
OPERATE IN
SECOND MODE

FIG. 6

DC/DC CONVERTER WITH RESONANT CONVERTER STAGE AND BUCK STAGE AND METHOD OF CONTROLLING THE SAME

BACKGROUND

1. Field

The disclosed concept pertains generally to direct current to direct current (DC/DC) converters and, more particularly, to multi-stage DC/DC converters. The disclosed concept also pertains to methods of controlling DC/DC converters.

2. Background Information

A DC/DC converter is configured to receive an input direct current (DC) voltage and convert it into one or more output DC voltages. In many applications, such as electric vehicle chargers, a DC/DC converter must be able to provide a relatively wide output voltage range. For example, the electric vehicle charging voltage range required by the CHAdeMo specification is 50-500 VDC. In other words, the maximum voltage in the range is ten times the minimum voltage in the range.

One type of DC/DC converter is an LLC resonant converter. An LLC resonant converter is a type of resonant converter whose resonant frequency is determined by two inductive components and one capacitive component. LLC resonant converters provide high efficiency, low levels of EMI emissions, high power density, and low cost. However, in prior LLC resonant converter designs, increasing the output voltage range detrimentally affects the efficiency of the LLC resonant converter by causing a larger shunt current in the primary side, thus increasing conduction loss.

Some prior DC/DC converter designs have used a buck stage in conjunction with an LLC resonant converter stage to obtain a wider output range. In one prior configuration, a buck stage is added after the LLC resonant converter stage, thus allowing a wider output voltage range.

In such DC/DC converter designs, the output voltage of the LLC resonant converter stage is controlled by changing its switching frequency and the output voltage of the buck stage is controlled by changing its duty cycle. Two methods have been used to control the output voltage of the DC/DC converter in these designs. For example, if the required output voltage is 50-500 VDC and the maximum current is 30 A, a first method fixes the output voltage of the LLC resonant converter stage to 500 VDC regardless of the load and regulates the output voltage with the buck stage. With this method, the LLC resonant converter stage can be optimized to have a high efficiency. However, the buck stage must have a relatively wide output range of 50-500 VDC and must be able to handle power up to 15 kW. Due to its hard switching, the loss in the buck stage is large. Additionally, the buck stage must be designed for a power of 15 kW, thus increasing its cost.

In a second method, the output voltage of the LLC resonant converter stage has a regulation range of 310-500 VDC at any load from OA to 30 A. If the required output voltage is above 310 VDC, the duty of the buck stage is set to 100% and the output voltage is regulated by the LLC resonant converter stage. If the required output voltage is below 310 VDC, the output voltage of the LLC resonant converter stage is set to 310 VDC or some other value at which the LLC resonant converter stage has a relatively high efficiency and the output voltage is regulated by controlling the duty cycle of the buck stage. In this second method, the efficiency of the LLC resonant converter stage is lower than the efficiency of the LLC resonant converter stage of the first method. However, the buck stage regulates a narrower range of voltages and has a lower power rating. Although the second method is more

efficient than the first method, there is room for further improvement in DC/DC converters.

SUMMARY

These needs and others are met by embodiments of the disclosed concept in which a DC/DC converter in which a processor apparatus is configured to perform one of: (a) fixing a switching frequency of a bridge circuit to a predetermined maximum switching frequency and controlling an output voltage by controlling a duty cycle of a buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage by controlling the switching frequency of the bridge circuit.

In accordance with aspects of the disclosed concept, a direct current to direct current (DC/DC) converter comprises: a resonant converter stage configured to receive an input voltage, the resonant converter stage including a bridge circuit having a number of pairs of power switches; a buck stage configured to output an output voltage and an output current, the buck stage being electrically connected in series with the resonant converter stage and including a buck switch; and a processor apparatus configured to sense the output voltage and the output current, and, based on the sensed output voltage and the sensed output current, to perform one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage by controlling the switching frequency of the bridge circuit.

Also in accordance with aspects of the disclosed concept, a method of controlling a DC/DC converter comprising a resonant converter stage including a bridge circuit having a number of pairs of power switches, and a buck stage electrically connected in series with the resonant converter stage and including a buck switch comprises: sensing an output voltage of the DC/DC converter; sensing an output current of the DC/DC converter; and based on the sensed output voltage and the sensed output current, performing one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit.

Also in accordance with aspects of the disclosed concept, a non-transitory computer readable medium storing one or more programs, including instructions, which when executed by a computer, causes the computer to perform a method of controlling a DC/DC converter comprising a resonant converter stage including a bridge circuit having a number of pairs of power switches, and a buck stage electrically connected in series with the resonant converter stage and including a buck switch comprises: sensing an output voltage of the DC/DC converter; sensing an output current of the DC/DC converter; and based on the sensed output voltage and the sensed output current, performing one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the disclosed concept can be gained from the following description of the preferred embodiments when read in conjunction with the accompanying drawings in which:

FIG. **1** is a circuit diagram of a DC/DC converter in accordance with an example embodiment of the disclosed concept.

FIG. **2** is a circuit diagram of a DC/DC converter in accordance with another example embodiment of the disclosed concept.

FIG. **3**A is an example graph of a gain vs. frequency characteristic of a resonant converter stage.

FIG. **3**B is an example graph of an output current and an output voltage of a resonant converter stage operated at a predetermined maximum switching frequency.

FIG. **4** is a block diagram of a processor apparatus in accordance with an example embodiment of the disclosed concept.

FIG. **5** is a flowchart of a method of controlling a DC/DC converter in accordance with an example embodiment of the disclosed concept.

FIG. **6** is a flowchart of a method of determining whether to operate a buck stage or a resonant converter stage of a DC/DC converter in accordance with an example embodiment of the disclosed concept.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Directional phrases used herein, such as, for example, left, right, front, back, top, bottom and derivatives thereof, relate to the orientation of the elements shown in the drawings and are not limiting upon the claims unless expressly recited therein.

As employed herein, the statement that two or more parts are "coupled" together shall mean that the parts are joined together either directly or joined through one or more intermediate parts.

As employed herein, the term "number" shall mean one or an integer greater than one (i.e., a plurality).

As employed herein, the statement that a component is on the "primary side of the DC/DC converter" and similar statements shall mean that the component is electrically connected, either directly or indirectly, to the primary winding of a transformer included in the DC/DC converter.

As employed herein, the statement that a component is on the "secondary side of the DC/DC converter" and similar statements shall mean that the component is electrically connected, either directly or indirectly, to the secondary winding of a transformer included in the DC/DC converter.

As employed herein, the term "switch" means any switch suitable for use in an electrical circuit. The term includes both mechanical type switches (e.g., without limitation, switches which physically separate contacts of the switch) and solid-state type switches (e.g., without limitation, transistors). The term also includes switch assemblies (e.g., without limitation, a transistor combined with a freewheel diode).

As employed herein, the term "processor" shall mean a programmable analog and/or digital device that can store, retrieve and process data; a controller; a control circuit; a computer; a workstation; a personal computer; a microprocessor; a microcontroller; a microcomputer; a central processing unit; a mainframe computer; a mini-computer; a server; a networked processor; or any suitable processing device or apparatus.

As employed herein, the phrase "predetermined maximum switching frequency of the bridge circuit" and similar phrases shall mean a predetermined frequency which is greater than the resonant frequency of a corresponding resonant DC/DC converter, and is the intended maximum switching frequency of the bridge circuit during normal operation of the corresponding DC/DC converter. The predetermined maximum switching frequency of the bridge circuit is not the maximum possible switching frequency of the bridge circuit or any switches such as power switches, thereof.

Referring to FIG. **1**, a DC/DC converter **1** in accordance with one non-limiting example embodiment of the disclosed concept is shown. The DC/DC converter **1** includes a resonant converter stage **100** which receives an input voltage V_{IN} and a buck stage **200** which outputs an output voltage V_{OUT} along with an output current I_{OUT}. The DC/DC converter **1** also includes a processor apparatus **300** which senses the output voltage V_{OUT} and output current I_{OUT} and controls operations of the resonant converter stage **100** and the buck stage **200** based on the sensed output voltage V_{OUT} and sensed output current I_{OUT}, which will be described in more detail below.

The example resonant converter stage **100** includes a bridge circuit **110**, a resonant network **120**, a transformer **130**, a rectifier circuit **140**, and a first filtering capacitor **150**. The example bridge circuit **110** receives the input voltage V_{IN} and drives the resonant network **120**. The bridge circuit **110** is a half-bridge circuit which includes one pair of power switches **111**,**112**. The processor apparatus **300** controls switching of the bridge circuit **110**, and in particular, the processor apparatus **300** controls the switching frequency of the bridge circuit **110**. A change in the switching frequency of the bridge circuit **110** causes a change in the gain of the resonant converter stage **100**. Thus, the processor apparatus **300** is able to control the gain of the resonant converter stage **100** by controlling the switching frequency of the bridge circuit **110**.

In the non-limiting example embodiment of FIG. **1**, the resonant network **120** includes the series combination of a first inductor **121** and a first capacitor **122**. The first inductor **121** may be a discrete component or it may be leakage inductance of the transformer **130**. The resonant network **120** is electrically connected between the bridge circuit **110** and the transformer **130**.

The transformer **130** includes a primary winding **131** and a secondary winding **132**. The primary winding **131** of the transformer **130** is electrically connected to the resonant network **120**. The transformer **130** also has a magnetizing inductance component. The magnetic inductance component may be caused by, for example and without limitation, a ferromagnetic core (not shown) of the transformer **130**. The transformer **130** isolates the primary and secondary sides of the resonant converter stage **100** from each other.

The secondary winding **132** of the transformer **130** is electrically connected to a rectifier circuit **140**. The secondary winding **132** of the transformer can be structured in any suitable manner such as, for example and without limitation, a single winding or double windings with a common tap. The rectifier circuit **140** rectifies the output of the secondary winding **132** of the transformer **130**. The rectifier circuit **140** can be structured in any manner suitable to rectify the output of the secondary winding **132** of the transformer **130**. For example and without limitation, the rectifier circuit **140** may be structured as a half-wave rectifier or a full-wave rectifier.

The first filtering capacitor **150** is electrically connected across the output of the resonant converter stage **100**. The first filtering capacitor **150** smoothes (e.g., reduces unevenness of) the output voltage of the resonant converter stage **100**.

The resonant converter stage **100** is configured as an LLC resonant converter. In an LLC resonant converter, the resonant frequency of the primary side is determined by two inductive components (e.g., without limitation, inductor **121** and the magnetizing inductance of the transformer **130**) and a capacitance (e.g., without limitation, capacitor **122**). However, it is contemplated that the principles of the disclosed concept can also be applied to other types of resonant converters. For example and without limitation, it is contemplated that resonant converter stage **100** can be modified to change the resonant converter stage **100** to an LCC resonant converter without departing from the scope of the disclosed concept. In an LCC resonant converter, the resonant frequency of the primary side is determined by one inductive component and two capacitive components. A capacitor (not shown) can be electrically connected in parallel with the primary winding **131** of the transformer **130** to convert the resonant converter stage **100** into an LCC resonant converter.

Additionally, it is contemplated that the resonant converter stage **100** can be structured as a series resonant converter (e.g., without limitation, the resonant network **120** includes an inductor **121** in series with a capacitor **122**), a parallel resonant converter (e.g., without limitation, the resonant network **120** includes an inductor (not shown) and capacitor (not shown) in parallel with the primary winding **131** of the transformer **130**), or a series parallel resonant converter (e.g., without limitation, the resonant network **120** includes an inductor **121** in series with a capacitor **122** and a capacitor (not shown) in parallel with the primary winding **131** of the transformer **130**) without departing from the scope of the disclosed concept.

The buck stage **200** is provided in series connection with the resonant converter stage **100**. The buck stage **200** includes a buck switch **201**, an inductor **202**, a diode **203**, and a second filtering capacitor **204**. The buck stage **200** receives the output voltage of the resonant converter stage **100** and outputs the output voltage V_{OUT}.

The buck switch **201** is electrically connected to the output of the resonant converter stage **100**. The processor apparatus **300** controls switching of the buck switch **201**. In particular, the processor apparatus **300** controls the duty cycle of the buck switch **201**. A change in the duty cycle of the buck switch **201** causes a change in the output voltage V_{OUT}. In particular, reducing the duty cycle of the buck switch **201** reduces the output voltage V_{OUT}. Thus, the processor apparatus **300** is able to control the output voltage V_{OUT} by controlling the duty cycle of the buck switch **201**.

A first end of the inductor **202** is electrically connected to the buck switch **201** and an opposite second end of the inductor **202** is electrically connected to the output of the buck stage **200**. The diode **203** is electrically connected between the first end of the inductor **202** and the negative output of the buck stage **200**. The second filtering capacitor **204** is electrically connected across the positive and negative outputs of the buck stage **200**.

As described above, the processor apparatus **300** senses the output voltage V_{OUT} and output current I_{OUT} and controls operations of the resonant converter stage **100** and the buck stage **200** based on the sensed output voltage V_{OUT} and sensed output current I_{OUT}. In more detail, the processor apparatus **300** determines whether to operate in a first mode or a second mode based on the sensed output voltage V_{OUT} and the sensed output current I_{OUT}. In the first mode, the processor apparatus **300** fixes the switching frequency of the bridge circuit **110** to a predetermined maximum switching frequency and controls the output voltage V_{OUT} by controlling the duty cycle of the buck switch **201**. The predetermined maximum switching frequency is a frequency that is selected to be higher than the resonant frequency of the resonant converter stage **100**. The efficiency of the resonant converter stage **100** may be taken into consideration when the predetermined maximum switching frequency is taken into account such that the predetermined maximum switching frequency is a switching frequency at which the resonant converter stage **100** operates at a relatively high efficiency. In one example embodiment, the predetermined maximum switching frequency is about 1.75 times the resonant frequency of the resonant converter stage **100**.

In the second mode, the processor apparatus **300** fixes the duty cycle of the buck switch **201** to a predetermined duty cycle (e.g., without limitation a 100% duty cycle) and controls the output voltage V_{OUT} by controlling the switching frequency of the bridge circuit **110**. When the duty cycle of the buck switch **201** is set to 100%, the power loss and voltage drop in the buck stage **200** is negligible.

To make the determination of whether to operate in the first mode or the second mode, the processor apparatus **300** determines a threshold voltage V_{TH} corresponding to the sensed output current I_{OUT} and compares the sensed output voltage V_{OUT} to the threshold voltage V_{TH}. If the sensed output voltage V_{OUT} is less than the threshold voltage V_{TH}, the processor apparatus **300** operates in the first mode and if the sensed output voltage V_{OUT} is greater than or equal to the threshold voltage V_{TH}, the processor apparatus **300** operates in the second mode. Derivation of threshold voltages V_{TH} corresponding to the sensed output currents I_{OUT} will be described below in connection with FIGS. **3**A and **3**B.

Referring to FIG. **2**, a circuit diagram of a DC/DC converter **1'** in accordance with another example embodiment of the disclosed concept includes a resonant converter stage **100'**, a buck stage **200**, and a processor apparatus **300**. The DC/DC converter **1'** of FIG. **2** is similar to the DC/DC converter **1** of FIG. **1**, except that the bridge circuit **110'** in the resonant converter stage **100'** of the DC/DC converter **1'** of FIG. **2** is a full-bridge circuit including two pairs of power switches **111**,**112**,**113**,**114**.

Referring to FIG. **3**A, a gain of the resonant converter stage **100** versus the switching frequency of the bridge circuit **110** for a number of output currents is shown. The gain of the resonant converter stage **100** is shown on the vertical axis and the ratio of the switching frequency f_s of the bridge circuit **110** to the resonant frequency f_r of the resonant converter stage **100** is shown on the horizontal axis. The gains for a number of output currents are shown on the graph. Additionally, an example predetermined maximum switching frequency **400** of the bridge circuit **110** is shown. At the predetermined maximum switching frequency **400**, which is greater than the resonant frequency f_r of the resonant converter stage **100**, the gain of the resonant converter stage **100** decreases as the output current increases.

FIG. **3**B is a plot of the output current I_{OUT} versus the output voltage V_{OUT} when the switching frequency of the bridge circuit **110** is set to the predetermined maximum switching frequency **400**. As shown in FIG. **3**B, the output voltage V_{OUT} decreases as the output current I_{OUT} increases. A boundary curve **401** is shown in FIG. **3**B. The boundary curve **401** includes the threshold voltages V_{TH} respectively corresponding to each output current I_{OUT}. The boundary curve **401** can be used by the processor apparatus **300** to determine whether to operate in the first mode or the second mode. Equal power curves are also shown in FIG. **3**B. Each point along a respective power curve represents the same amount of power. For example, each point along the 5.6 kw power curve represents an output power of 5.6 kw.

The area to the left of the boundary curve **401** (hereinafter referred to as the "buck area" **402**) corresponds to the first mode and the area to the right of the boundary curve **401** (hereinafter referred to as the "resonant converter area" **403**) corresponds to the second mode. If the output voltage V_{OUT} and output current I_{OUT} fall in the buck area **402**, then the processor apparatus **300** operates in the first mode. If the output voltage V_{OUT} and output current I_{OUT} fall in the resonant converter area **403**, then the processor apparatus **300** operates in the second mode.

In one example embodiment, the processor apparatus **300** makes the determination of whether the sensed output voltage V_{OUT} and sensed output current I_{OUT} fall in the buck area **402** or the resonant converter area **403**, and thus determines whether to operate in the first mode or the second mode by determining the threshold voltage V_{TH} corresponding to the sensed output current I_{OUT} and comparing that threshold voltage V_{TH} to the sensed output voltage V_{OUT}. If the sensed output voltage V_{OUT} is less than the threshold voltage V_{TH}, then the processor apparatus **300** operates in the first mode, and if the sensed output voltage is greater than or equal to the threshold voltage V_{TH}, the processor apparatus operates in the second mode. However, it will be understood that any suitable method of determining whether the sensed output V_{OUT} and sensed output current I_{OUT} fall in the buck area **402** or the resonant converter area **403** may be employed without departing from the scope of the disclosed concept.

In one non-limiting example embodiment, the DC/DC converter **1** has a range of about 50-500 VDC (i.e., the output voltage range corresponding to the CHAdeMo specification) and a maximum output current of about 30 A. Additionally, when the bridge circuit **110** is switched at the predetermined maximum switching frequency, the output voltage of the resonant converter stage **100** ranges from about 310 VDC at 0 A to 180 VDC at 30 A. Under these conditions, the processor apparatus **300** operates in the first mode at any output voltage V_{OUT} below about 180 VDC and in the second mode at any output voltage V_{OUT} above about 310 VDC. For output voltages V_{OUT} between about 180 VDC and about 310 VDC, the processor apparatus **300** determines which mode to operate in based on whether the output voltage is greater than or less than the threshold voltage V_{TH} corresponding to the output current I_{OUT}.

In this example, the power that the buck stage **200** should be rated for is 5.6 kw. As shown in FIG. **3**B, for a range of about 50-500 VDC and a maximum output current of about 30 A, the highest power curve that touches the buck area **402** is the 5.6 kw power curve. Thus, the power rating for the buck stage **200** is lower compared to previous control methods. As such, the cost and size of the buck stage **200** can be reduced compared to designs using previous control methods. Furthermore, the decreased input voltage results in lower switching losses in the buck switch **201**, thus providing a more efficient design compared to designs using previous control methods. As a result, the DC/DC converters **1**,**1'** provide relatively high power and wide voltage range at a relatively low cost, small size, and high efficiency.

FIG. **4** is a block diagram of a processor apparatus **300** in accordance with one non-limiting example embodiment of the disclosed concept. The processor apparatus **300** includes a processor **301**, isolated gate drivers **302**, a sensing interface **303**, and an interface **304**.

The processor **301** determines whether to operate in the first mode or the second mode and controls the bridge circuit **110** and the buck switch **201** through the isolated gate drives **302** accordingly. The sensing interface **303** is configured to receive the output voltage V_{OUT} and output current I_{OUT} and to communicate information on the output voltage V_{OUT} and output current I_{OUT} to the processor **301**. The interface **304** is configured to communicate with an external control device **305** which may, for example, instruct the processor **301** to set the output voltage V_{OUT} to a certain level. The processor apparatus **300** may also include additional sensing interfaces (not shown) configured to receive the input voltage V_{IN} and/or the output voltage of the resonant converter stage **100**.

FIG. **5** is a flowchart of a method of controlling the DC/DC converter **1** which may be implemented in, for example and without limitation, the processor apparatus **300**. In operation **S1**, information of the output voltage V_{OUT} and output current I_{OUT} is received. In operation **S2**, it is determined whether to operate in the first mode or the second mode. If it is determined to operate in the first mode, operation **S3** is performed in which the bridge circuit **110** switching frequency is set to the predetermined maximum switching frequency. In operation **S4**, the duty cycle of the buck switch **201** is controlled to control the output voltage V_{OUT}. The process then returns to operation **S1**.

If it is determined to operate in the second mode, operation **S5** is performed in which the buck switch **201** is set to a predetermined duty cycle (e.g., without limitation, a 100% duty cycle). In operation **S6**, the switching frequency of the bridge circuit **110** is controlled to control the output voltage V_{OUT}. The process then returns to operation **S1**.

FIG. **6** is a flowchart showing the method of determining whether to operate in the first mode or the second mode. The method may be implemented in, for example and without limitation, the processor apparatus **300**. In operation **S10**, the threshold voltage V_{TH} corresponding to the sensed output current I_{OUT} is determined. In operation **S11**, it is determined whether the sensed output voltage V_{OUT} is greater than or equal to the threshold voltage V_{TH}. If the sensed output voltage V_{OUT} is not greater than or equal to the threshold voltage V_{TH}, the operation **S12** is performed in which the DC/DC converter **1** is operated in the first mode. If the sensed output voltage V_{OUT} is greater than or equal to the threshold voltage V_{TH}, the operation **S13** is performed in which the DC/DC converter **1** is operated in the second mode. As described above, in the first mode, the switching frequency of the bridge circuit **110** is set to a predetermined maximum switching frequency and the output voltage V_{OUT} is controlled by controlling the duty cycle of the buck switch **201**. In the second mode, the duty cycle of the buck switch **201** is fixed to a predetermined duty cycle (e.g., without limitation a 100% duty cycle) and the output voltage V_{OUT} is controlled by controlling the switching frequency of the bridge circuit **110**.

The disclosed concept can also be embodied as computer readable codes on a tangible, non-transitory computer readable recording medium. The computer readable recording medium is any data storage device that can store data which can be thereafter read by a computer system. Non-limiting examples of the computer readable recording medium include read-only memory (ROM), non-volatile random-access memory (RAM), CD-ROMs, magnetic tapes, floppy disks, disk storage devices, and optical data storage devices.

While specific embodiments of the disclosed concept have been described in detail, it will be appreciated by those skilled in the art that various modifications and alternatives to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of the disclosed concept which is to be given the full breadth of the claims appended and any and all equivalents thereof.

What is claimed is:

1. A direct current to direct current (DC/DC) converter comprising:

a resonant converter stage configured to receive an input voltage, the resonant converter stage including a bridge circuit having a number of pairs of power switches;

a buck stage configured to output an output voltage and an output current, the buck stage being electrically connected in series with the resonant converter stage and including a buck switch; and

a processor apparatus configured to sense said output voltage and said output current, and, based on the sensed output voltage and the sensed output current, to perform one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling said output voltage by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling said output voltage by controlling the switching frequency of the bridge circuit.

2. The DC/DC converter of claim **1**, wherein the predetermined duty cycle of the buck switch is a 100% duty cycle.

3. The DC/DC converter of claim **1**, wherein the bridge circuit is a half-bridge circuit including one pair of power switches.

4. The DC/DC converter of claim **1**, wherein the bridge circuit is a full-bridge circuit including two pairs of power switches.

5. The DC/DC converter of claim **1**, wherein the resonant converter stage further includes a resonant network driven by the bridge circuit, a transformer having a primary winding and a secondary winding, the primary winding being electrically connected to the resonant network, a rectifier circuit electrically connected to the secondary winding, and a filtering capacitor electrically connected to the rectifier circuit.

6. The DC/DC converter of claim **1**, wherein the buck stage further includes a diode electrically connected to the buck switch, an inductor electrically connected to the buck switch, and a filtering capacitor electrically connected to the inductor.

7. The DC/DC converter of claim **1**, wherein the processor apparatus determines a threshold voltage corresponding to the sensed output current; wherein the processor apparatus compares the sensed output voltage to the determined threshold voltage; and wherein when the sensed output voltage is less than the determined threshold voltage, the processor apparatus performs said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling said output voltage by controlling the duty cycle of the buck switch, and when the sensed output voltage is greater than the determined threshold voltage, the processor apparatus performs said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling said output voltage by controlling the switching frequency of the bridge circuit.

8. The DC/DC converter of claim **1**, wherein the output voltage of the DC/DC converter has a range of about 50-500 VDC; and wherein the processor apparatus performs said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling said output voltage by controlling the duty cycle of the buck switch when the output voltage is less than about 180 VDC and performs said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling said output voltage by controlling the switching frequency of the bridge circuit when the output voltage is greater than about 310 VDC.

9. The DC/DC converter of claim **1**, wherein the resonant converter stage is structured as at least one of a series resonant converter, a parallel resonant converter, and a series parallel resonant converter.

10. The DC/DC converter of claim **1**, wherein resonant converter stage is structured as at least one of an LLC resonant converter and an LCC resonant converter.

11. A method of controlling a DC/DC converter comprising a resonant converter stage including a bridge circuit having a number of pairs of power switches, and a buck stage electrically connected in series with the resonant converter stage and including a buck switch, the method comprising:

sensing an output voltage of the DC/DC converter;

sensing an output current of the DC/DC converter; and

based on the sensed output voltage and the sensed output current, performing one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit.

12. The method of claim **11**, wherein the predetermined duty cycle of the buck switch is a 100% duty cycle.

13. The method of claim **11**, further comprising:

determining a threshold voltage corresponding to the sensed output current;

comparing the sensed output voltage to the determined threshold voltage;

performing said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling the duty cycle of the buck switch when the sensed output voltage is less than the determined threshold voltage; and

performing said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit when the sensed output voltage is greater than the determined threshold voltage.

14. The method of claim **11**, further comprising:

performing said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling the duty cycle of the buck switch when the output voltage is less than about 180 VDC; and

performing said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit when the output voltage is greater than about 310 VDC,

wherein the output voltage of the DC/DC converter has a range of about 50-500 VDC.

15. The method of claim **11**, wherein the resonant converter stage is structured as at least one of a series resonant converter, a parallel resonant converter, and a series parallel resonant converter.

16. The method of claim **11**, wherein resonant converter stage is structured as at least one of an LLC resonant converter and an LCC resonant converter.

17. A non-transitory computer readable medium storing one or more programs, including instructions, which when executed by a computer, causes the computer to perform a method of controlling a DC/DC converter comprising a resonant converter stage including a bridge circuit having a number of pairs of power switches, and a buck stage electrically connected in series with the resonant converter stage and including a buck switch, the method comprising:

sensing an output voltage of the DC/DC converter;

sensing an output current of the DC/DC converter; and

based on the sensed output voltage and the sensed output current, performing one of: (a) fixing a switching frequency of the bridge circuit to a predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling a duty cycle of the buck switch, and (b) fixing the duty cycle of the buck switch to a predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit.

18. The non-transitory computer readable medium of claim 17, wherein the predetermined duty cycle of the buck switch is a 100% duty cycle.

19. The non-transitory computer readable medium of claim 17, wherein the method further comprises:

determining a threshold voltage corresponding to the sensed output current;

comparing the sensed output voltage to the determined threshold voltage;

performing said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling the duty cycle of the buck switch when the sensed output voltage is less than the determined threshold voltage; and

performing said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit when the sensed output voltage is greater than the determined threshold voltage.

20. The non-transitory computer readable medium of claim 17, wherein the method further comprises:

performing said fixing the switching frequency of the bridge circuit to said predetermined maximum switching frequency and controlling the output voltage of the DC/DC converter by controlling the duty cycle of the buck switch when the output voltage is less than about 180 VDC; and

performing said fixing the duty cycle of the buck switch to said predetermined duty cycle and controlling the output voltage of the DC/DC converter by controlling the switching frequency of the bridge circuit when the output voltage is greater than about 310 VDC,

wherein the output voltage of the DC/DC converter has a range of about 50-500 VDC.

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